REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
11 April 2003	Technical Paper	

4. TITLE AND SUBTITLE

Thruster Imaging Analysis for Control of a Solar Concentrator

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

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5d. PROJECT NUMBER
1011

5e. TASK NUMBER
0062

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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8. PERFORMING ORGANIZATION REPORT NUMBER

AFRL-PR-ED-TP-2003-094

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

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10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S NUMBER(S)
AFRL-PR-ED-TP-2003-094

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

20030616 049

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Sheila Benner
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(include area code)*
Unclassified	Unclassified	Unclassified	A		(661) 275-5963

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18

FILE

MEMORANDUM FOR PRS (In-House Publication)

FROM: PROI (STINFO) 21 Apr 2003

SUBJECT: Authorization for Release of Technical Information, Control Number: **AFRL-PR-ED-TP-2003-094**

6458 Beasley, Joe (PRSO), "Thruster Imaging Analysis for Control of a Solar Concentrator"

Joint Propulsion Conference **(Statement A)**

(Huntsville, AL, July 2003) (Deadline: 15 May 2003)

Thruster Imaging Analysis for Control of a Solar Concentrator

Abstract:

This paper discusses results of image processing of solar thruster images for use in controlling a solar concentrator. Video capture images of an SRS solar thruster are analyzed to determine focal spot parameters and the best method of determining placement of the solar focal spot to provide maximum power transfer to the thruster. Since the intensity of the light is distorted by shadows and specular reflection, location of the focal spot is non-trivial with absorber information obscured in the specular reflection, that focal spot information needs to be de-convolved using Digital Signal Processing (DSP) from the scattering distribution of the thruster absorber. The paper discusses characterizing the specular reflection of the thruster secondary concentrator and discusses its effect on the determination of focal spot location.

Introduction:

Solar Thermal Propulsion (STP) is a promising concept for use in an Orbital Transport Mission, a deep space mission, or other upper stage space missions requiring high Specific Impulse engines. Since the energy for propulsion is available to the spacecraft in orbit, an STP system would not have to carry propellant and oxidizer to produce energy for the upper stage unit. Only an atomic or molecular propellant such as Hydrogen would be needed on the upper stage. The STP system heats up Hydrogen in the thruster and then expands the Hydrogen through a nozzle to produce the thrust required by the vehicle. Thus the thrust-to-weight efficiency of the STP system is much better (up to two times better) than the equivalent chemical upper stage as less non-payload mass is needed in the STP system for the same amount of thrust to be developed.[i]

A major difference between a chemical-type thruster/spacecraft and an STP thruster/spacecraft is that the STP spacecraft has the added task of controlling the solar concentrators. Not only does the spacecraft need to properly point the concentrators towards the sun while the engine maneuvers in space, it needs to protect them from the exhaust of the spacecraft. For the protection requirement to be met, off-axis concentrators protect the concentrators while providing required power for the thruster throughout its maneuvering regime. The final requirement is that the focal cone should always be positioned on the aperture closest to the nozzle for effective heat transfer to the propellant.[ii]

The current concept for the solar concentrators for a solar thruster is two off axis paraboloid concentrators connected to a central thruster. Each concentrator is connected to the central thruster with a hexapod unit offering 6 degree of freedom (DOF) control. The 6 DOF needed are yaw, pitch, roll, x, y, and z. Optical analysis for a flight demo concentrator system indicates that the required angular pointing accuracy is 0.1 deg and the translation accuracy should be 0.1 inch. Coarse alignment is obtained using an on axis detector that brings the spacecraft and concentrators into a general alignment with the sun. Coarse alignment brings the focal cone into rough alignment with the desired aperture on the thruster.[iii] Concentrator control should provide optimum energy transfer to the solar thruster while protecting the concentrator and spacecraft from the dynamic behavior of the whole system.

Control over the focal spot location on the thruster aperture drives the search for a method of first locating the focal spot on the thruster and deriving concentrator control inputs to reposition the focal spot to optimize power or heat transfer. The sensor used to determine focal spot location is an important part of the overall control mechanism. The sensor used in the experiment performed in this paper was a CCD camera.

Previous work on this topic[iv], presented at the ASME 2003 International Solar Energy Conference , indicated that a short time Fourier transform(STFT) on the image data would lead to the required focal spot location information for data from a computer simulated off-axis concentrator. Also, information in that paper indicated that the STFT was not sufficient in cases where the movement of the concentrator did not move the focal spot in X and Y, but only changed the maximum value. The purpose of this effort is to move from the computer simulation to actual thruster data and to extend the analysis to include wavelets as an extension to the STFT.

Experiment and Setup:

The setup for the concentrator and data collection system is shown in Figure XX1. A 1m X 2 m elliptical concentrator was utilized for the concentrator as that was the style of concentrator available at SRS Technologies in Huntsville, AL. Figures A3 and A4 in the appendix show photos of the actual concentrator and light source. This type of concentrator was acceptable as the data that was to be collected was only CCD camera shots of the thruster on "sun" and only a focal spot on the thruster was needed. A divergent point source located at the other focus of the ellipse was used to simulate the light from the sun. Because the concentrator was elliptic, the point source had to be located at the far focus (because light rays emitted from one focus of an ellipse get reflected through the other focus) while the thruster was located at the near focus as shown in the figure. Figure XX2 shows a schematic (2 Dimensional) of the setup in figure XX1. Appendix A presents photographs of all of the equipment and setup. A scissor jack platform was used to vary the vertical position of the point source at the far focus. Figure XX2 also shows the axes positioning for the source, which is then used in the production of the images presented later. The zero height position of the source is at the focus location of 16.25 inches above the floor of the setup building.
The data collection system consisted of an ST-6 CCD Camera manufactured by SBIG in Santa Barbara, CA and a Sony Vaio computer running SBIG's proprietary image collection software. This software allowed the user to set various parameters of the camera. One parameter under user control, was the exposure time for the camera to view the scene. Exposure times were important as they determined whether the CCD registered a good image or washed the image out by overexposure. The images presented later in this paper indicate the exposure times used. The camera used a 40 mm f.1 lens with a small aperture to provide good depth of field. The CCD was spaced from the lens to give the best image focus at 1 meter from the thruster. The CCD in the camera measured 23 X 27 micro-meters and had 375 pixels by 241 pixels. As figure XX1 presents, the camera was mounted on the concentrator supporting ring approximately 64 inches away from the thruster surface.

Test Apparatus

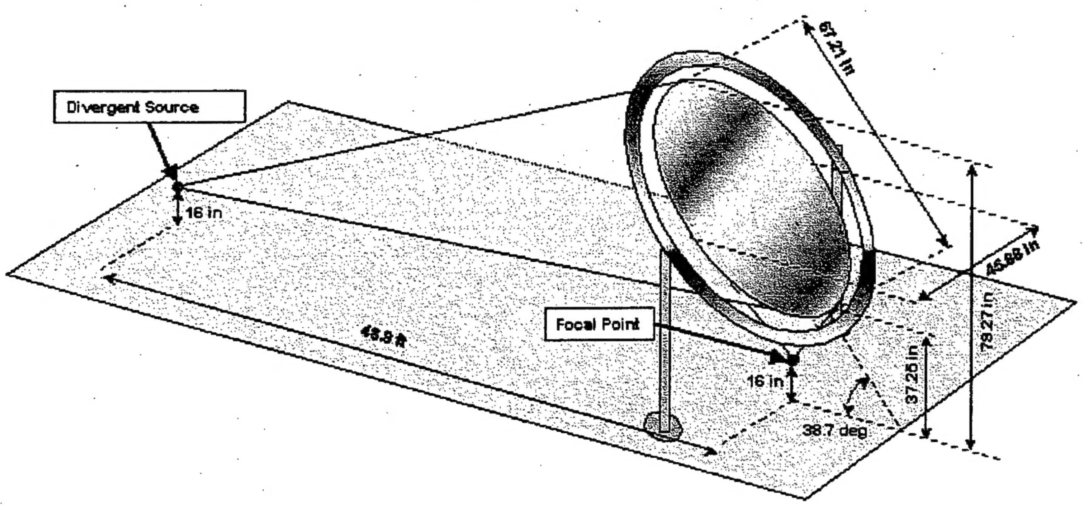

Figure XX1 Test Setup (ideal spacing for concentrator used).

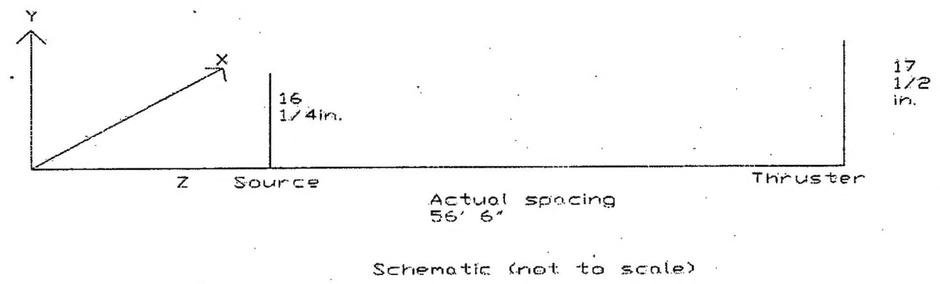

Figure XX2. 2 Dimensional schematic of test setup (actual spacing in tests shown).

Method of Data Collection:

Since the algorithms must be able to resolve changes in translation of 0.1 inch and 0.1 degrees, the calculation for an angle of 0.1 degree was performed for the setup shown in figure XX1, and was found to be about 1 inch. Therefore, the source light was moved in 1 inch increments in both the vertical and horizontal directions. A standard measuring tape was used to measure the placement of the source light; measurements were measured to 1 inch lines and could be + or - an eighth of an inch. Once the position of the source was set, the camera was commanded to take an image of the thruster. Each image included taking a "dark" image with the camera element blocked to set a zero image. Each image was taken for 0.1 seconds. At the time that the experiment was performed, it was thought that the analysis to be performed would provide enough information regarding the specular reflections, that no other exposure times were utilized. Table XX1 shows each of the data runs. The maximum vertical limit of the scissors jack was 4 5/8 inches while the maximum horizontal position was 3 inches off of focus. The horizontal limit was a result of how much the scissors jack and point source could be moved on the block before the unit would fall off of the block.

Run Number	Offset Vertical (inches)	Offset Horizontal (inches)	Exposure Time	Comments
1	0	0	0.1 s	Start
2	1	0	0.1 s	
3	2	0	0.1 s	
4	3	0	0.1 s	
5	4	0	0.1 s	
6	5	0	0.1 s	
7	0	0	0.1 s	Source off
8	0	1	0.1 s	
9	1	1	0.1 s	
10	2	1	0.1 s	
11	3	1	0.1 s	
12	4	1	0.1 s	
13	0	2	0.1 s	
14	1	2	0.1 s	

Run Number	Offset Vertical (inches)	Offset Horizontal (inches)	Exposure Time	Comments
15	2	2	0.1 s	
16	3	2	0.1 s	
17	4	2	0.1 s	
18	0	3	0.1 s	Source off
19	0	3	0.1 s	
20	1	3	0.1 s	
21	2	3	0.1 s	
22	3	3	0.1 s	
23	4	3	0.1 s	

Table XX1: Test information for experiment.

Image Processing:

Mathworks MATLAB software with the Image Processing Toolbox and Wavelet Toolbox was used to perform the image analysis. Each image was loaded into the MATLAB program along with the one source-off image taken. The source-off image was taken to capture the ambient lighting effects in the SRS high bay.

The methods used to process the images consisted of several steps. Each image was first enhanced to provide contrast adjustment. Contrast enhancement was necessary as each image had a very limited range of intensities, as evidenced in a representative histogram shown in figure XX3, so the images' ranges of intensities were stretched to fill the dynamic range. Then each image was filtered using a Gaussian low-pass filter. After low-pass filtering, each image was then filtered using a LaPlacian high-pass filter (LOG—LaPlacian of Gaussian) to provide image edge enhancement. The LoG filtering was thought to help eliminate the histogram problems encountered in the images taken for the experiment. Although, the LoG filter removes intensity bias, caused by changes in illuminations, it did not help improve the histogram of the images[v]. This last image, in effect a band-passed image, with the edges enhanced and the noise from the LaPlacian filter reduced by the low-pass filtering was used for further analysis.[vi] Finally, the pre-processed and filtered source-off image was subtracted from each image to remove the effects of the ambient lighting. The second method used the same pre-processing steps as the first one but substituted an average filter instead of the LOG filter. Each method will be discussed as to its effectiveness in the next section.

Image Analysis:

A histogram of the image with a 4-inch vertical offset is shown in figure XX3 and indicates the need to perform contrast enhancement, as most of the pixels lie in the lower portion of the histogram. Figures XX4 and XX5 shows the image and histogram after histogram equalization. Figure XX6 shows the source-off image after enhancement. Figure XX7 shows the final image after LOG filtering and subtraction. It is this final image that will be used in the image analysis. Figure XX8 shows the final enhanced image when the average filter is used for the enhancement process. Each of the images shown in figures XX7 and XX8 were then analyzed with the STFT to find out whether the location of the focal spot could be determined. Figure XX9 shows the result from using the STFT on the data from LoG filtering of the image.

Results and Conclusion:

Since LoG filtering is basically a band pass operation on the images, the STFT produces the band pass response of the image and does not provide information for determining focal spot location using the STFT. The STFT results from using the averaging filter were more interesting as far as their use in determining the location of the focal spot. In both the X direction and the Y direction, pixel numbers for the maximum of the focal spot were determined with ease. The STFT in X and Y directions are shown in figures XX10 and XX11 and show that ~~if~~ the maximums in each direction on figure XX10 and XX11 would, respectively, produce the X pixel number and Y pixel number of the location of the focal spot. The information

provided from those two figure calculations could then be processed to provide concentrator control commands.
A conclusion from this work is that the averaging filter was shown to be better suited when the STFT was used to determine focal spot location. Although the LoG filtering was not as useful, it could still be useful for procedures that do not perform Fourier-type operations, such as spatial-domain operations involving gradients, feature extraction, etc.
Histogram processing is also needed when each image is taken to make sure that the intensities fully populate the histogram. Instead of taking images at multiple 1-inch increments, fewer increments and more exposures should be taken to be sure that the histograms are more fully populated. A study of the specular reflection seen at the absorber needs to be accomplished, as the current imaging techniques and analysis do not properly account for the specular reflections. Plus filtering techniques beyond LoG filtering needs to be studied to determine if additional filtering techniques are able to handle the specular reflections and also provide a better means of determining the location of the focal spot.

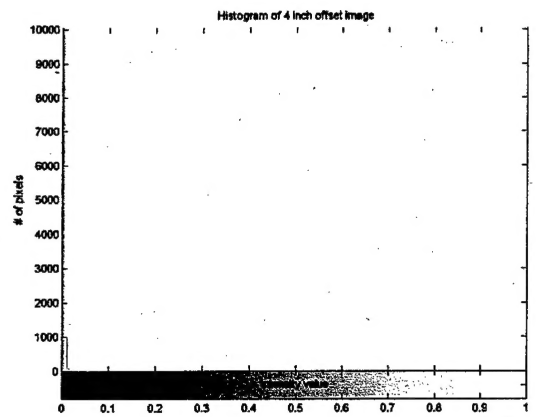

Figure XX3 Histogram of 4 inch vertical offset.

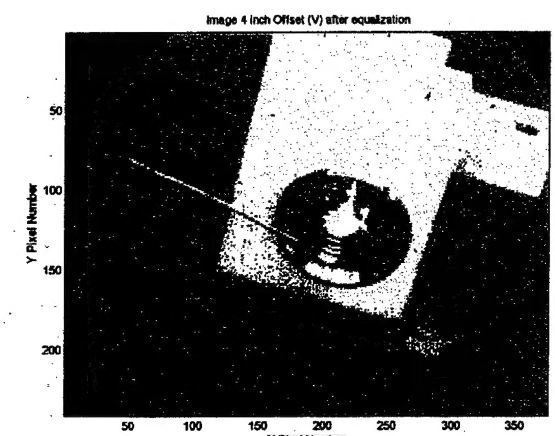

Figure XX4 Image after histogram equalization.

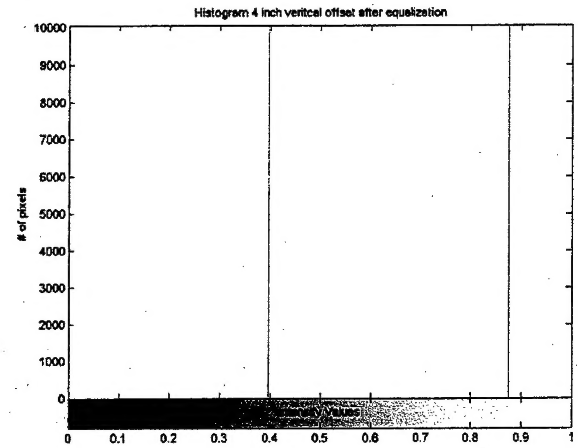

Figure XX5 Histogram of image after equalization.

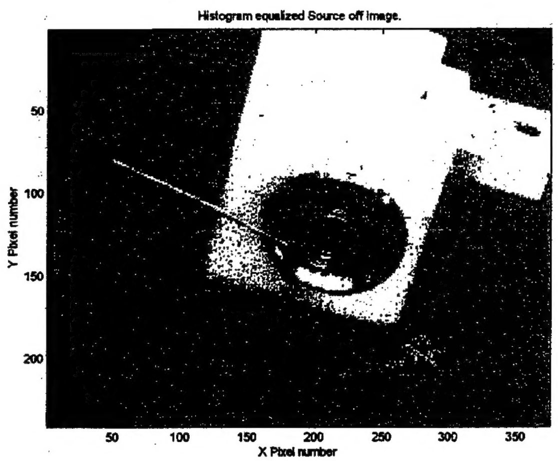

Figure XX6 Image of source-off after equalization.

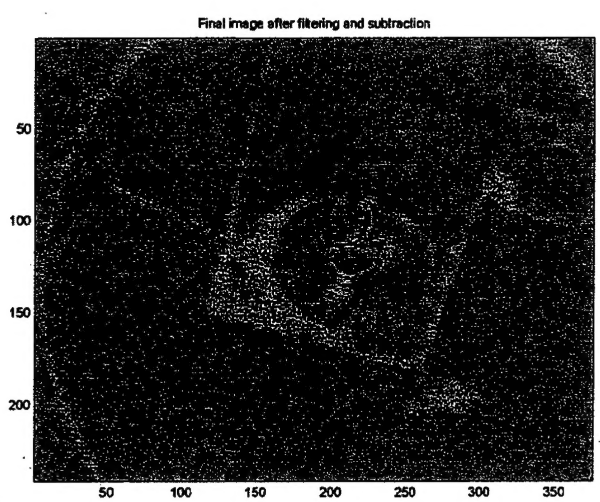

Figure XX7 Final image after LoG enhancement and subtraction of source-off image.

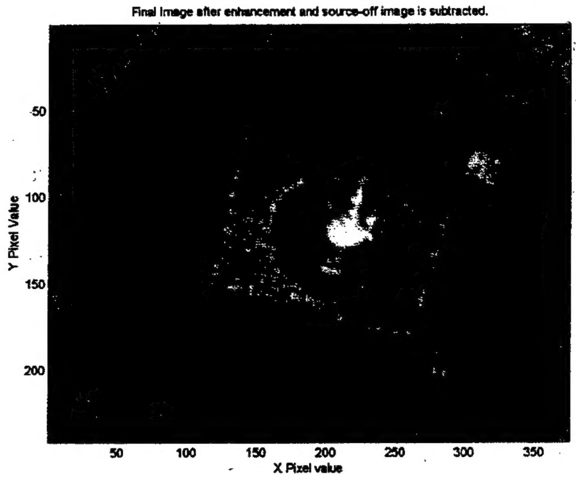

Figure XX8 Final Image after enhancement and subtraction.

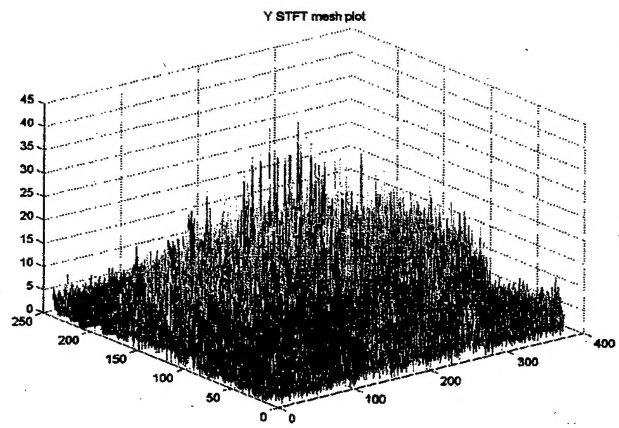

Figure XX9 Plot of STFT in Y direction for the LoG filtered version.

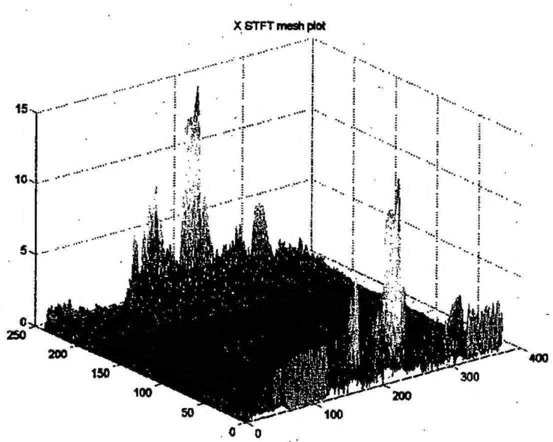

Figure XX10 X direction STFT magnitude.

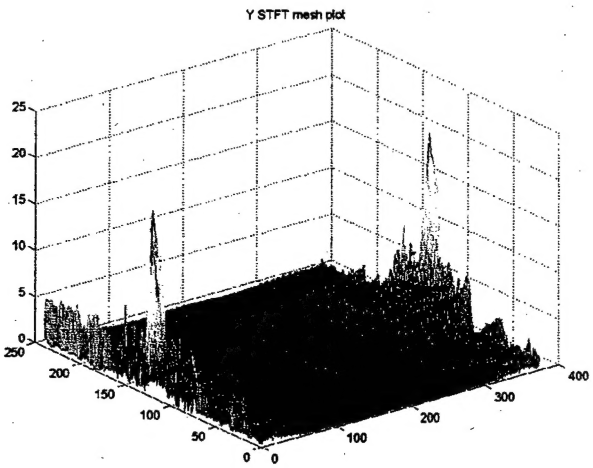

Figure XX11 Y STFT magnitude plot.

APPENDIX A:

Various Photos from the experimental setup

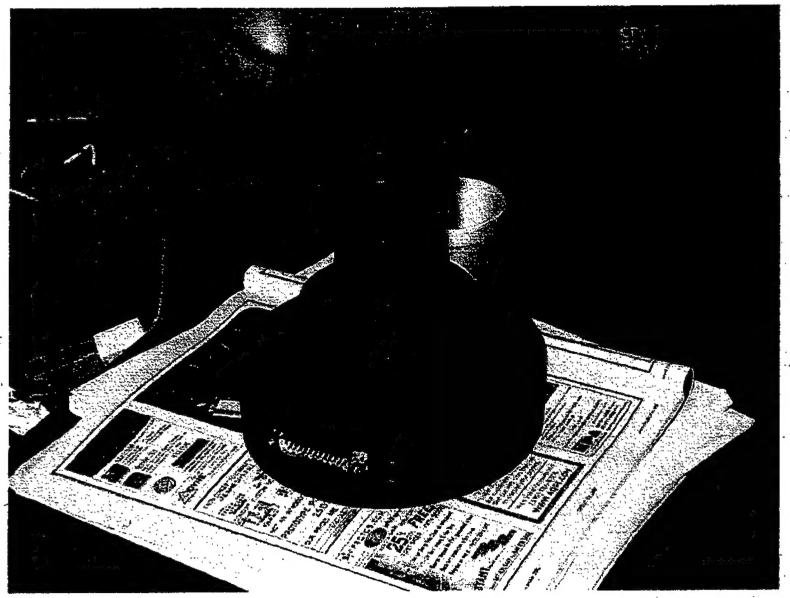

Figure A1 CCD Camera used ST-6 camera from SBIG.

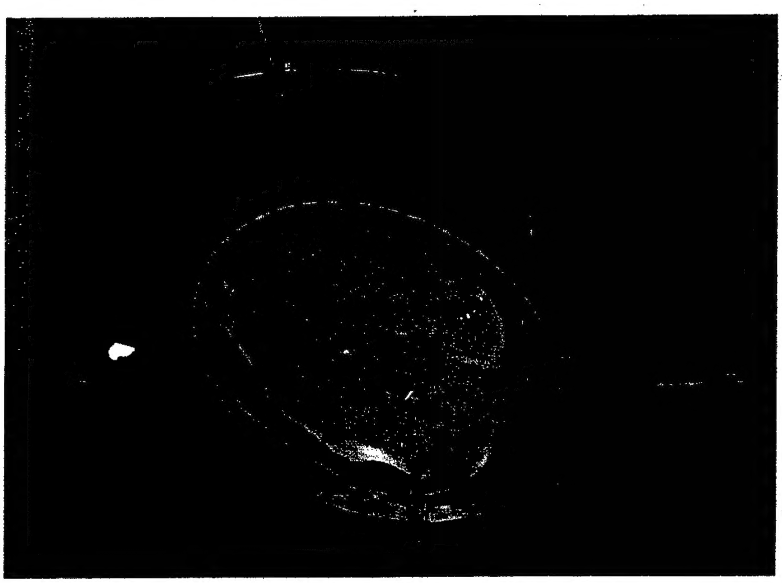

Figure A2 Camera location on strut for concentrator.

Figure A3 Concentrator in holder with camera on "sun."

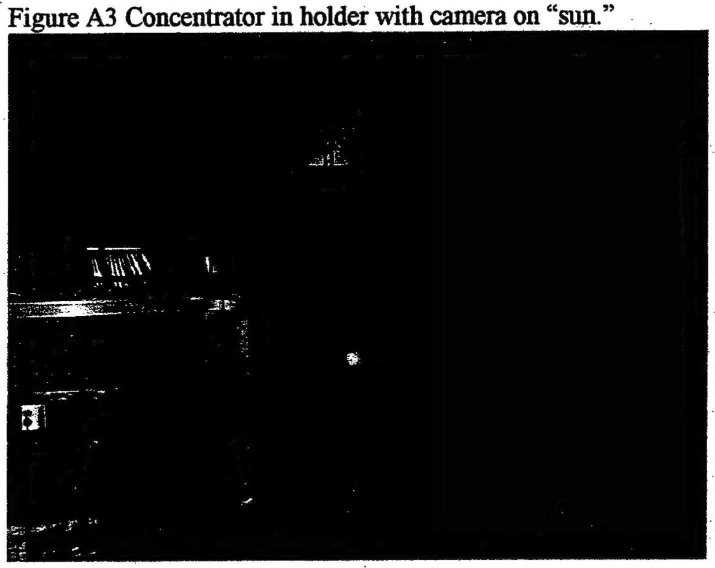

Figure A4 Point source at far focus showing black curtains to reduce specular reflection from floor.

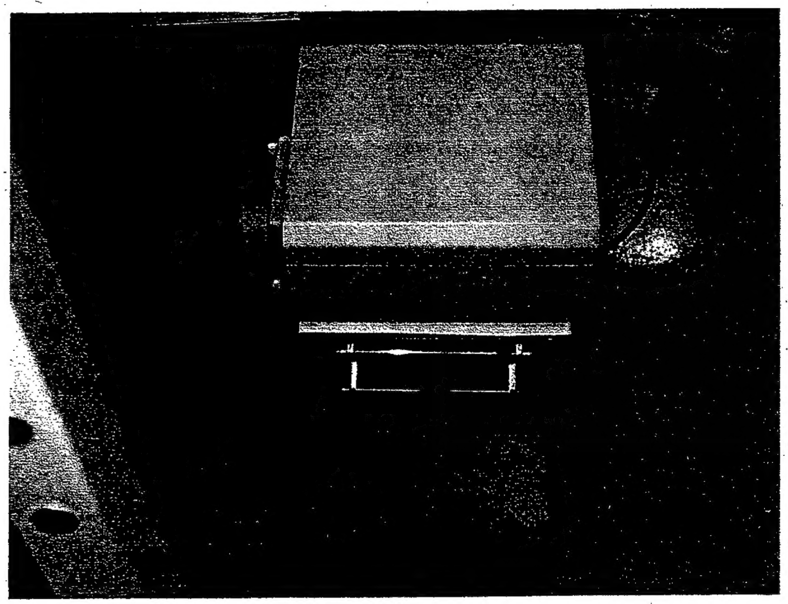

Figure A5 Shot of point source and scissors jack on block to match focus location.

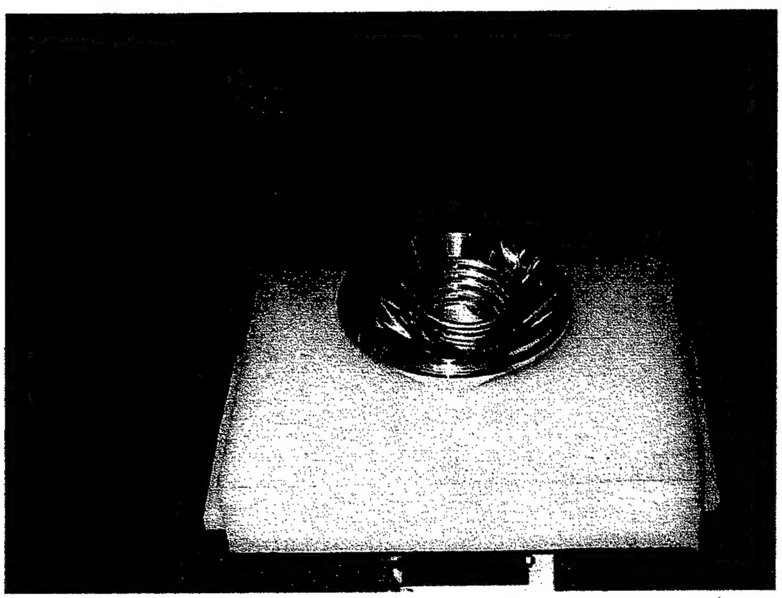

Figure A6 Thruster holding table.

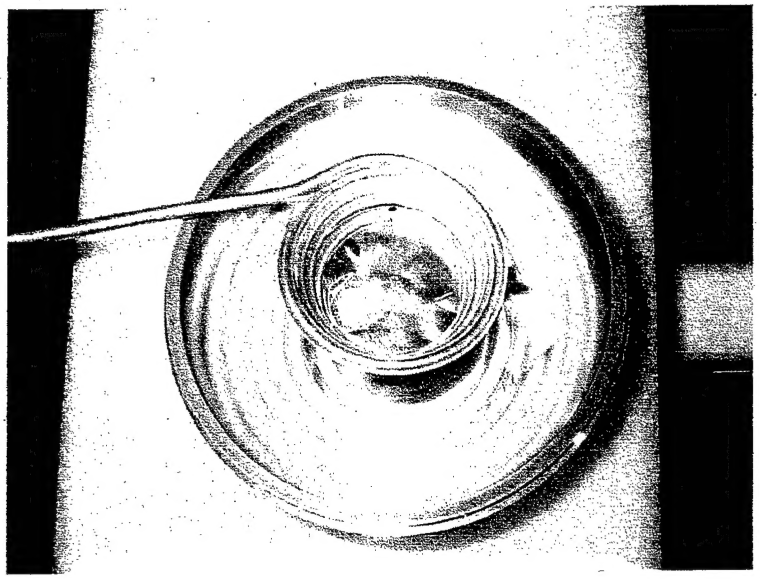

Figure A7 Top of thruster showing absorber and secondary concentrator.

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[i] Holmes, Dr. Michael R., "Ideal Performance of Off-Axis Paraboloid Concentrators for Solar-Thermal Propulsion," ASME 1996
[ii] Ibid.
[iii] Wassom, Dr. Steven R., "Focus Control System for Solar Thermal Propulsion," 2000 International ADAMS User Conference.
[iv] Beasley, Joseph N., "Digital Signal Processing Techniques for Positioning of Off-axis Solar Concentrators," ASME ISEC 2003
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[vi] Gonzalez, Rafael, C., Richard E. Woods, Digital Image Processing, 2nd Ed., Pearson Education, 2002.